Time-sensitive Complex Networked Control Systems

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Presentation Outline

- From networked control systems to time-sensitive complex networked control systems
  - What a networked control system?
  - What is a complex system?
  - What is a time sensitive application?
  - What is a time sensitive complex networked control system?
- Illustrations and experience sharing
  - Smart Grids
  - Intelligent transportation systems
- My two cents
  - Challenges
  - Tools
- Summary

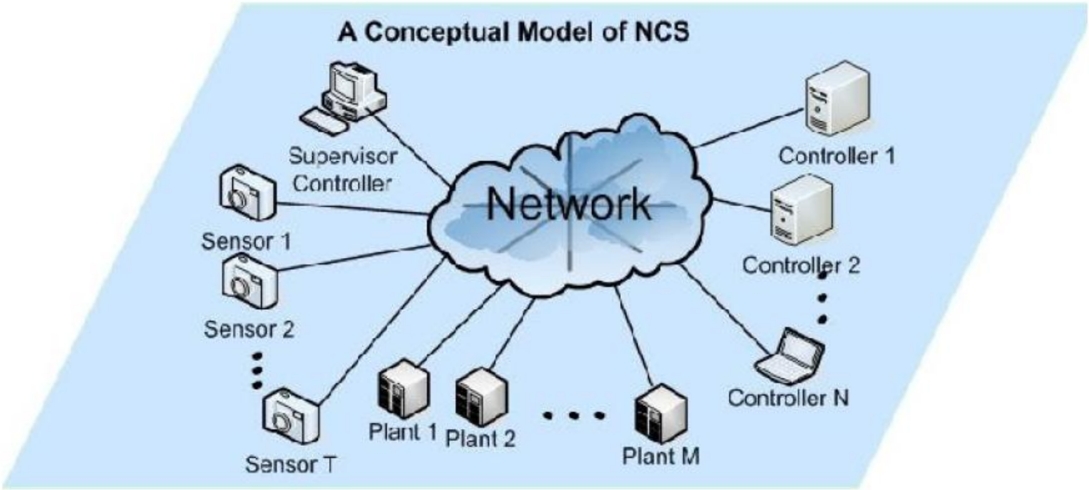
Networked Control Systems

What is Networked Control System (NCS)?

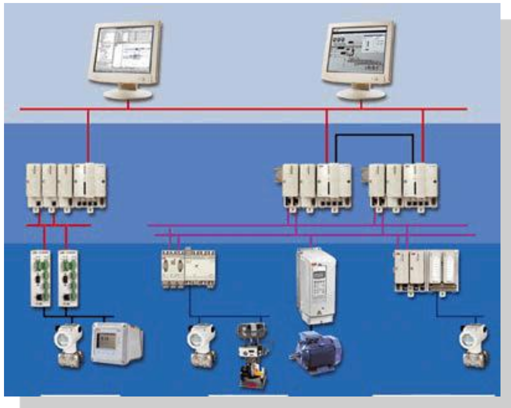
- NCS is a control system wherein the control loops are closed through a real-time network.
- Control and feedback signals are exchanged among the system's components in the form of information packages through a network.

Basic Elements

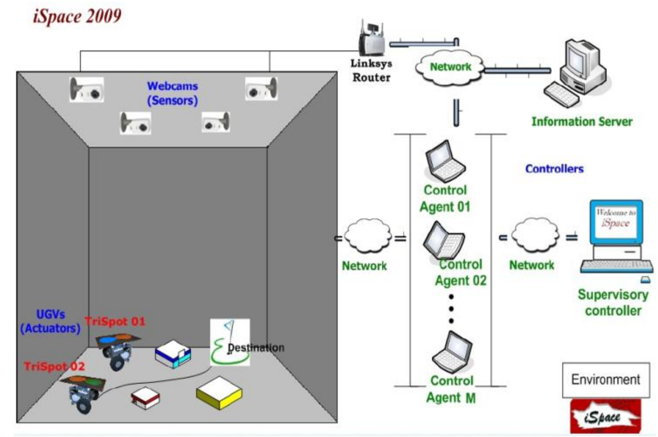
- Sensors
- Controllers
- Actuators
- Communication network



Networked Control System Applications

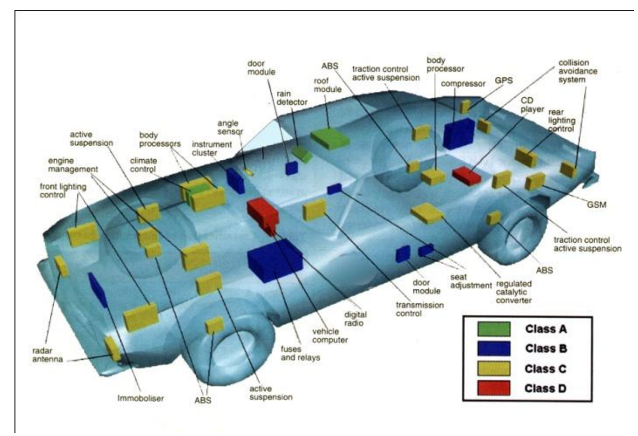


Manufacturing systems – Fieldbus



Intelligent spaces

Telemedicine



Vehicles - CAN

Complex Networks

- A complex network

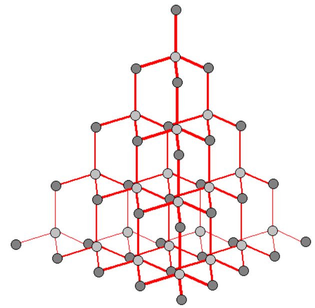
  a network with non-trivial topological features—features that do not occur in simple networks such as lattices or random graphs. Patterns of connection between the elements are neither purely regular nor purely random. http://en.wikipedia.org/wiki/Complex_network

- Real-world complex networks:
  - » Computer networks (e.g. the Internet);
  - » Social networks (e.g. the human webs);
  - » Biological networks (e.g. the ecosystems);
  - » …

- How is it different from "others"?
  - Multiple types of vertex
  - Multiple types of edge
  - Combined patterns of connection: neither purely regular nor purely random

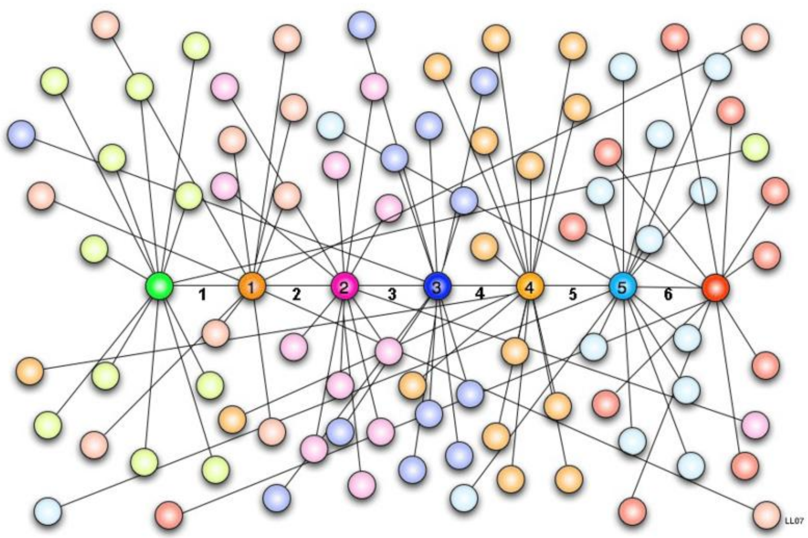
Complex Network?

A Diamond crystal lattice network



No

A Human Network



Yes

Complex Network: examples

- Social network
  - ➢ Six steps separated from another person on Earth
  - ➢ It's a small world

- Airline network
  - ➢ Nodes: airports
  - ➢ Edges: the flight route

Complex Networked Control Systems (CNCS)

- Some typical salient Features
  - Large-Scale
  - Dynamic Network Structure
    - Nodes may arrive/leave at any time
  - Distributed
    - Sensing/actuating/computation is distributed over several nodes
  - Cooperative
    - Information sharing among nodes
  - Layered
    - Each layer consists of its own set of rules/timing requirements while strongly connected to other layers
  - System-wide Coordination and Control
  - Emergent
    - Overall behavior in a layer emerges out of local interactions among nodes
  - Secured

CNCS Application Domains

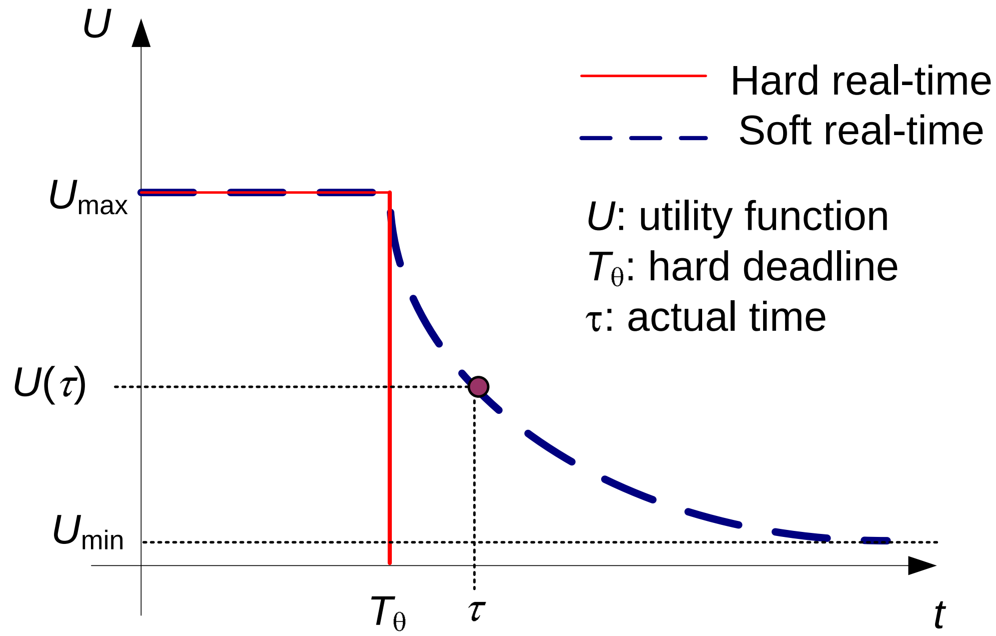
- Energy
  - Network Security Layer, Fault identification layer,
  - Balancing power production vs. consumption
  - Remotely controlled devices for ensuring local distribution
- Transportation
  - Safety and Congestion Management Layer (Higher level control, communication to infrastructure)
  - Interactions between nearby vehicles (Wireless)
  - Electronic devices within a vehicle (CAN)
- Molecular Processes
  - Networks of interactions (transcription networks)
  - Interactions between molecular species
  - Micro-fluidic devices to control the cellular environment
- and many others

CNCS Challenges

- Highly unstructured environments with large uncertainties
- Synchronization & Consensus
- Communication constraints
- Development of scalable solutions
- Modeling at different levels of abstraction and moving seamlessly from one to the other
- Understanding the effect of control commands on emergent behavior
- Prediction of the network behavior, stability analysis for a large-scale complex network
- Flexible/adaptive design to accommodate the dynamic network structure

Time-sensitive applications

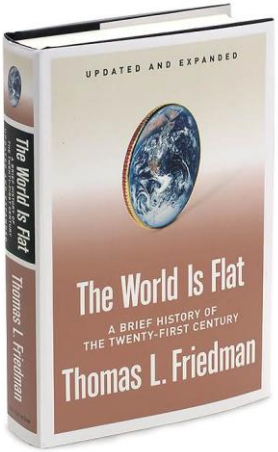
- Hard real-time control
  - E.g.: Catching a flight
- Soft real-time control
  - E.g., Going to watch a movie



Thomas L. Friedman's Quotes (The World is Flat)

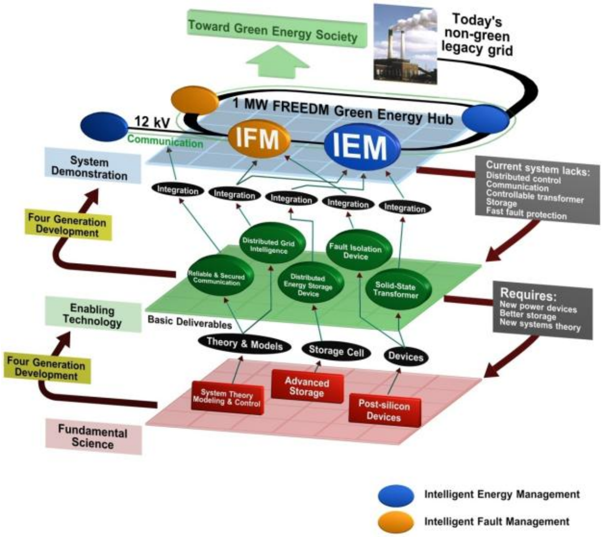
- "Globalization 3.0 (~2000) is shrinking the world from a size small to a size tiny and flattening the playing field at the same time. [Friedman, 2003]

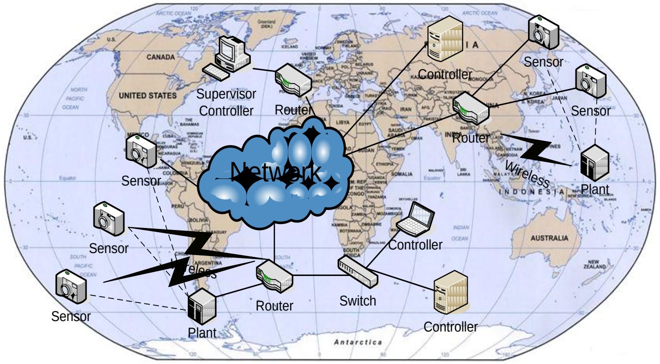
  - The flat-world platform is the product of a convergence of the personal computers (which allowed every individual suddenly to become the authors of his or her own context in digital form) with fiber-optic cable (which suddenly allowed all those individuals to access more and more digital content around the world for next to nothing) with the rise of work flow software (which enabled individuals all over the world to collaborate on the same digital content from anywhere, regardless the distances between them).
  - We are now connecting all the knowledge centers on the planet together into a single global network.



Implications Time-sensitive CNCS

- Enabling and enpowering individuals and small groups of sensors, actuators and controllers go global easily and seamlessly.
- Unique character – the newfound power for individuals (sensors, actuators, controllers) to collaborate/cooperate globally to solve local challenging problems (that cannot be solved otherwise)
- Provide optimized system performance with low cost through distributed information utilizations
- Enable real-time monitoring, control and operation globally with distributed local information
- Could usher in an amazing era of prosperity, innovation, and collaboration, by integrating distributed sensors, actuators, and controllers around the world.





Time-sensitive Complex Networked Control System Examples

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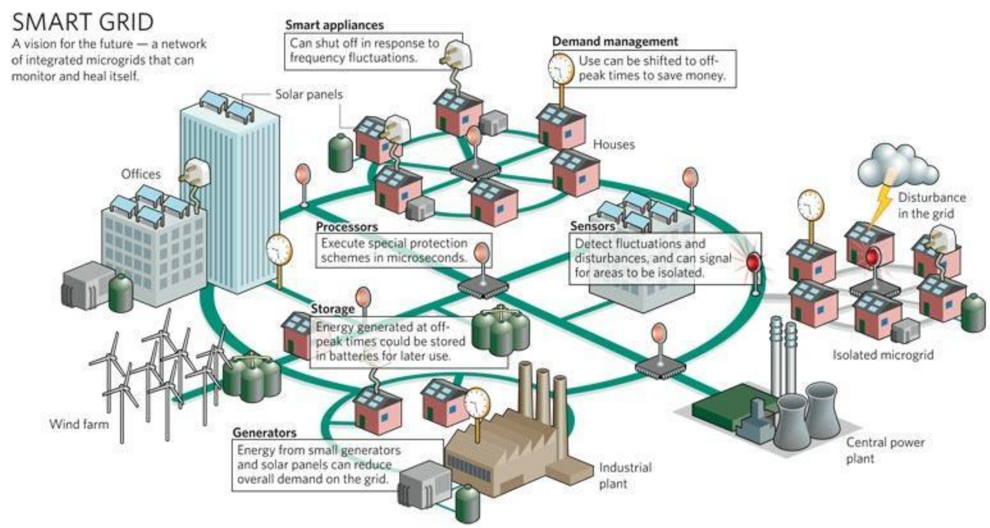
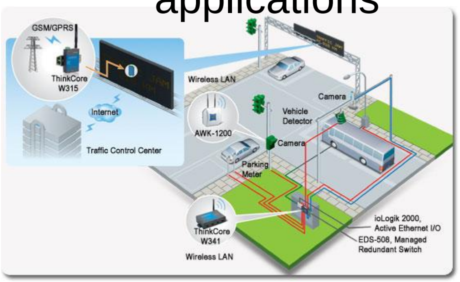
Smart grid

- Multiple networks
- Multiple power generations
- Multiple operators
- Varying level of communication and coordination
- Energy management and Fault management (time-critical) applications





Large scale

Intelligent Transportation System

- Vehicle detection
- Collision avoidance (Time-critical)
- Advanced Traffic Management System
- Traffic and Environment Monitoring
- In-vehicle Control and Monitoring
- V2V and V2G Communication

Future Renewable Electric Energy Delivery and Management (FREEDM) Systems

FREEDM: Generation-III Engineering Research Center (ERC) inaugurated in Sept.'08 with an initial 5 yr extendable to 10 yrs $40 million grant. Coalition of 7 universities, about 50 faculty members & 250 students, 60+ industry partners & 3 national laboratories

Director: Dr. Alex Huang, Progress Energy Professor

Center Vision: To develop an efficient and revolutionary energy distribution grid – an "internet" for energy distribution

- Utilizes revolutionary ***power electronics technology*** and ***information technology***
- Integrates distributed and scalable alternative energy sources and storage with existing power systems
- Automates the management of the ***load, generation*** and ***storage***

FREEDM Systems Center

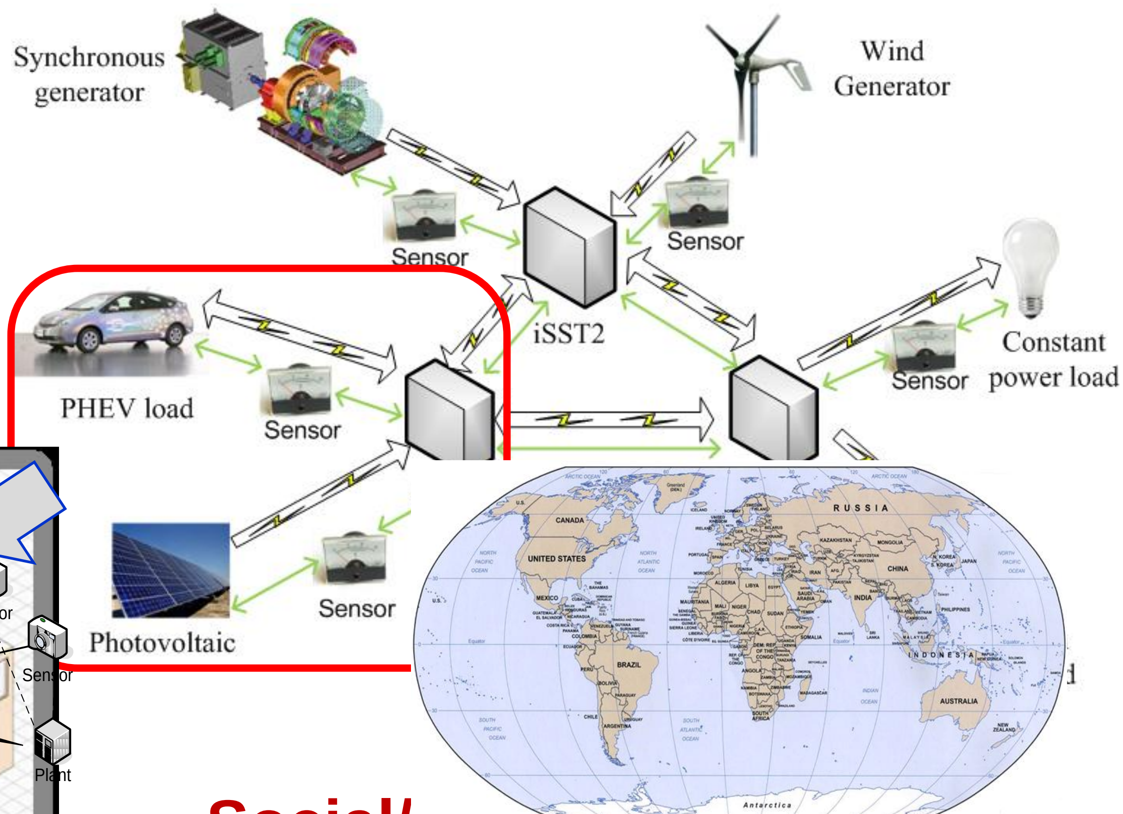
http://www.freedm.ncsu.edu/

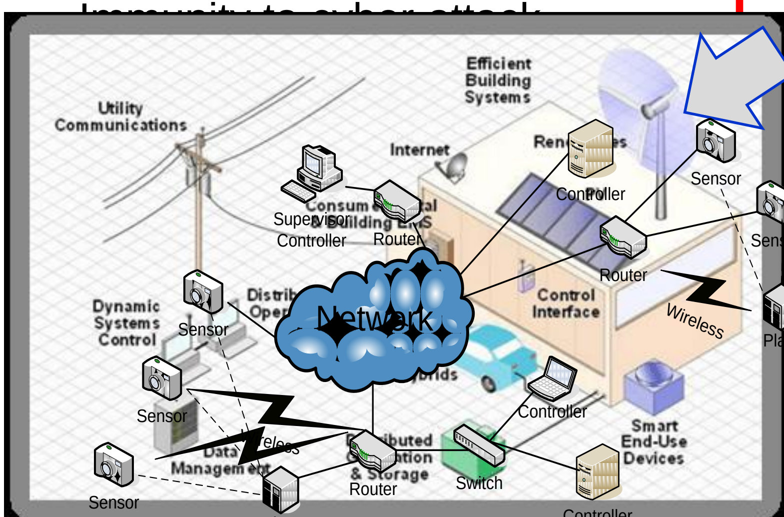
FREEDM System: a very *smart* Smart Grid

Goal of Smart Grid: ***Intelligent power delivery*** with *optimal* efficiency, effectiveness, power quality, resilience, reliably, availability, etc.

Features

- Self healing property
- Delivery of high power quality
- Customized power usages
- Effective and efficient energy systems
- Immunity to cyber attack

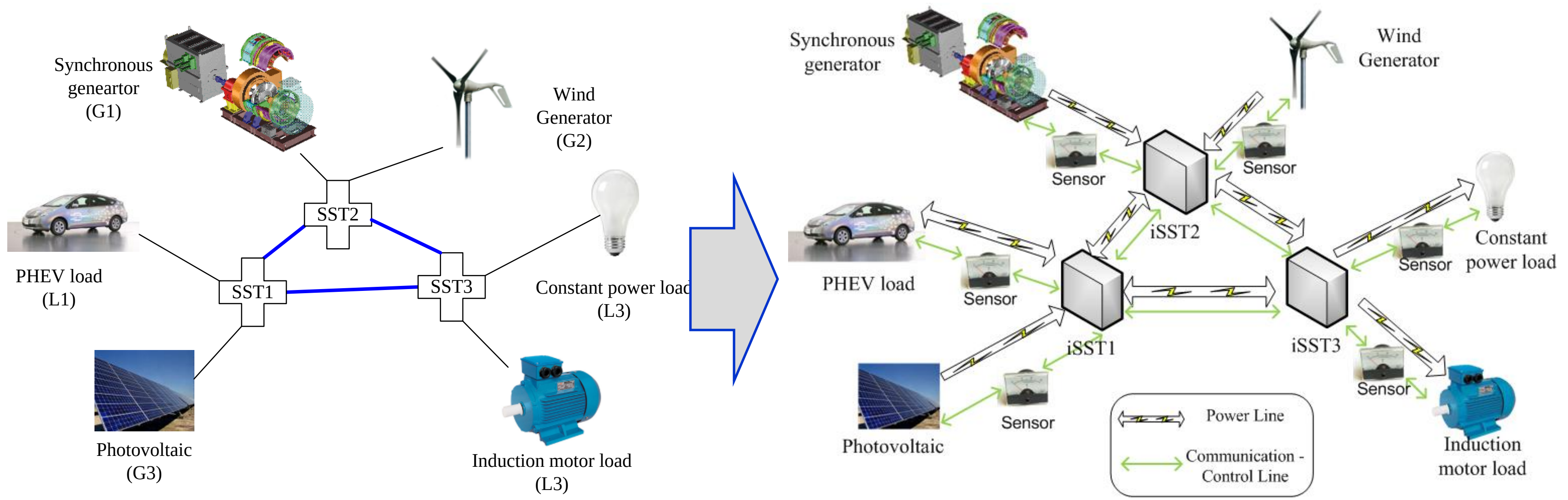




Picture form EPRI

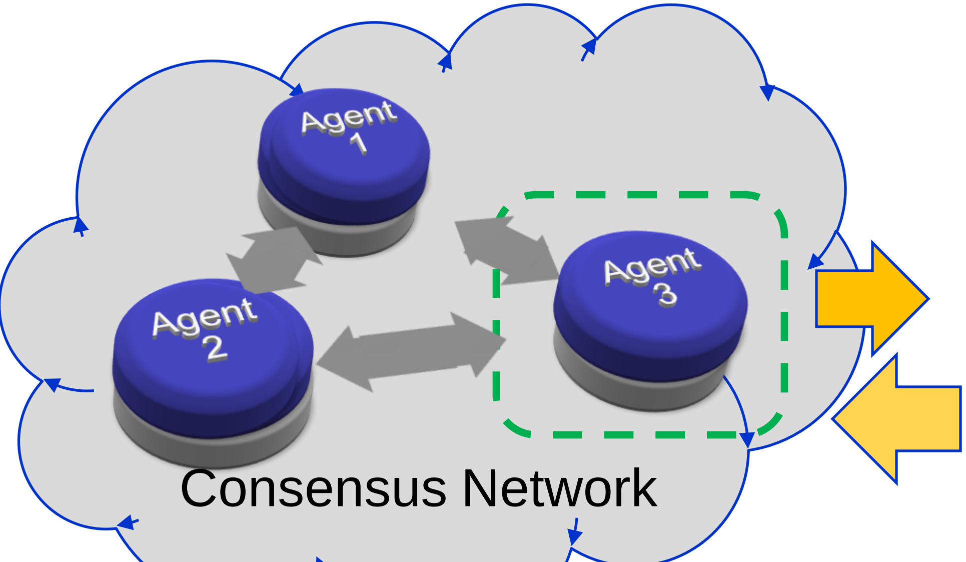
Social/economical-network inspired approach

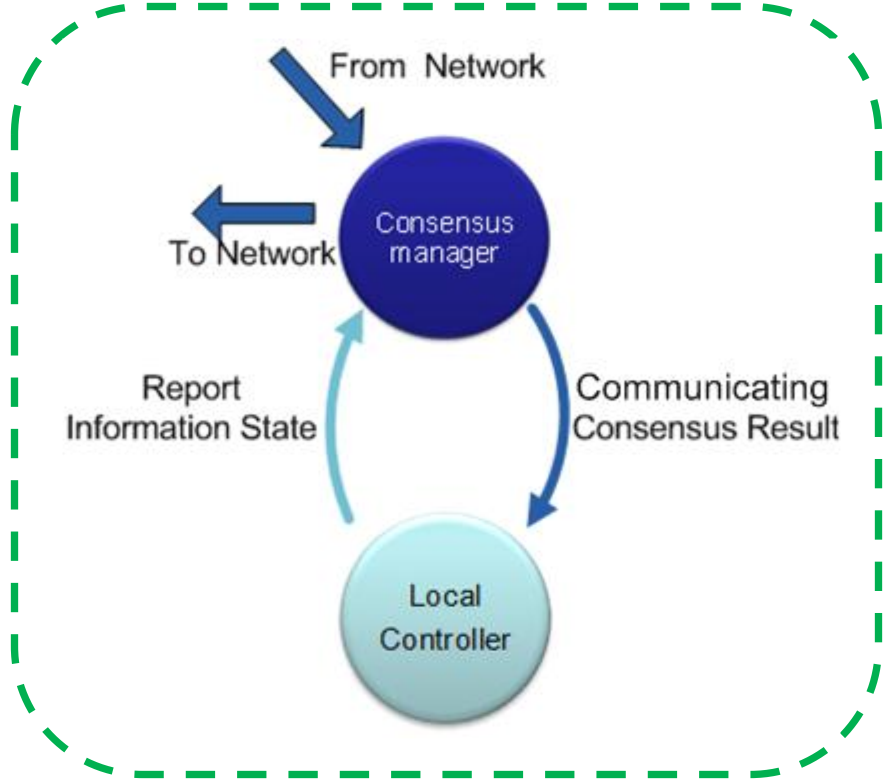
Current work: Application of consensus algorithms on FREEDM systems



- Formulate the consensus algorithms for the FREEDM systems with both continuous time models and discrete event models
- Design high performance and reliable consensus algorithms for FREEDM systems
- Interacting with other groups
  - NCSU (communication network resilience, delay, reconfiguration, NCSU green hub models, distributed control algorithms – Dr. Mueller, Dr. Jiang, Dr. Baran)
  - MST (MST FREEDM testbed, load balancing algorithms – Dr. McMillin, Dr. Crow)
  - ASU (SST models, optimization – will establish closer interactions)

How can consensus be reached?





Independent Physical Systems

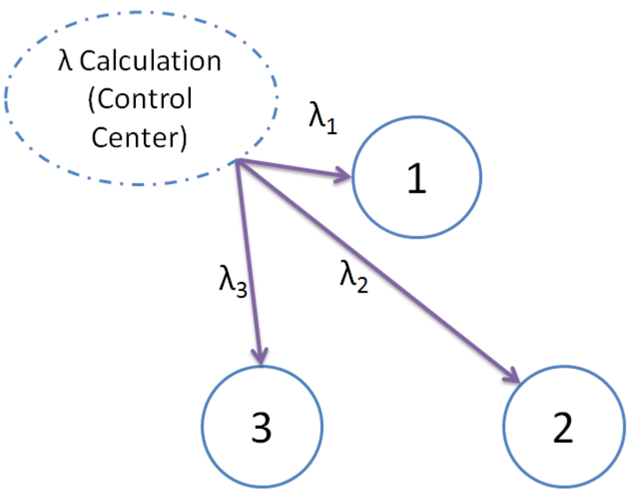
Each of them follow their own dynamic

A sufficient condition for reach consensus: If there is a directed spanning tree* exists in the communication network, then consensus can be reached. [1]

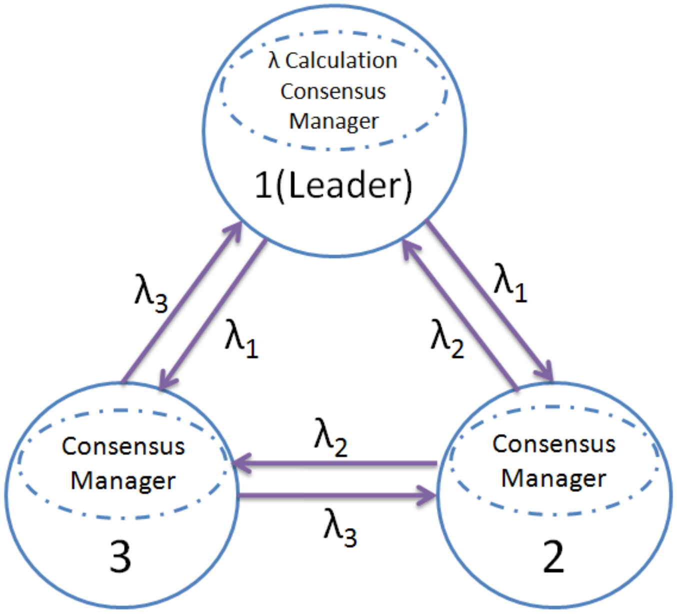
*Spanning tree: a minimal set of edges that connect all nodes

Incremental Cost Consensus Algorithm

- **Objective:**
  - » Solve the conventional Economic Dispatch Problem (EDP) in a distributed manner

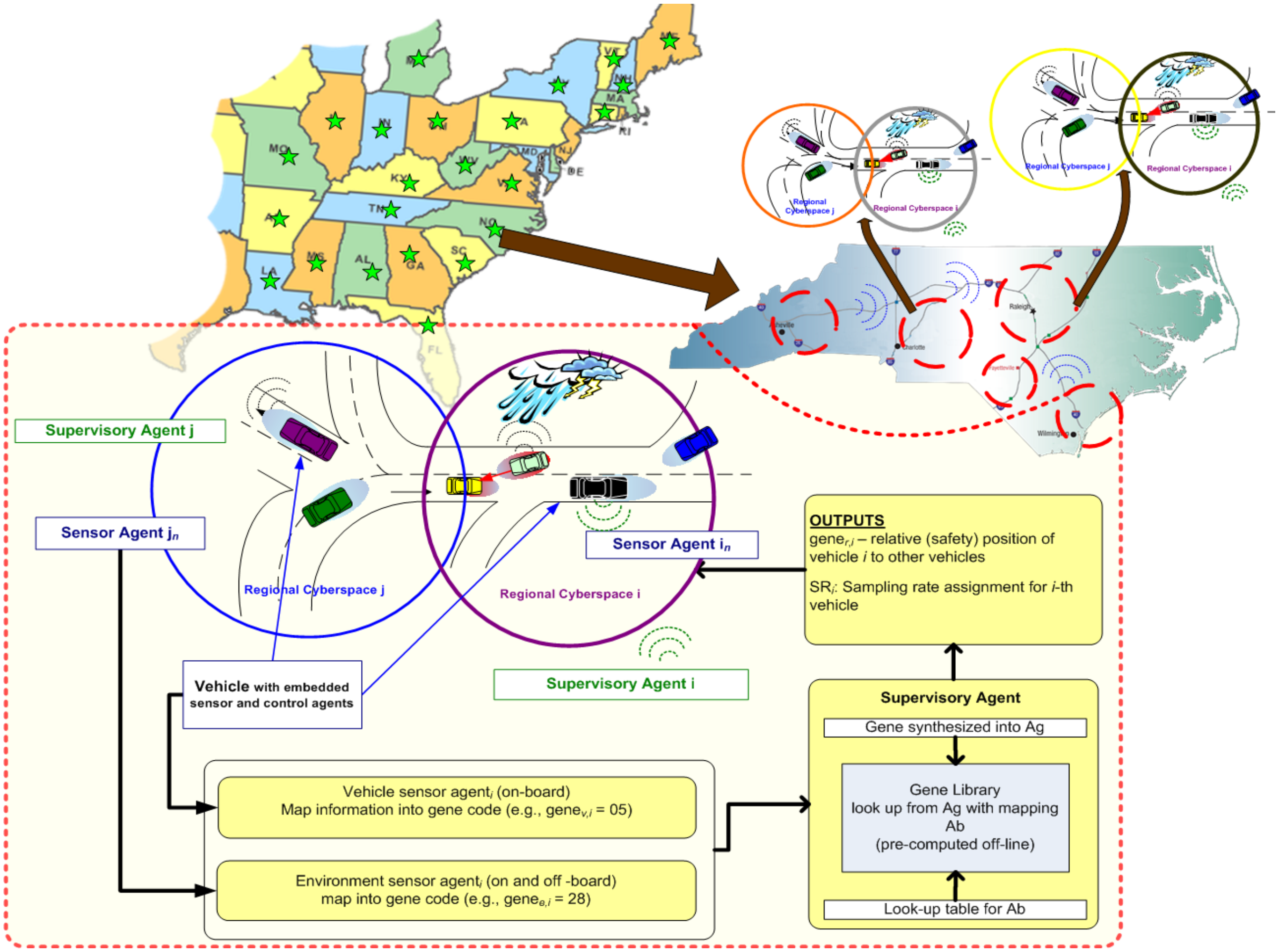


Conventional Central Controlled Communication Topology for a 3-bus system



Distribute Controlled Incremental Cost Consensus Network

Intelligent Transportation Systems (ITS)

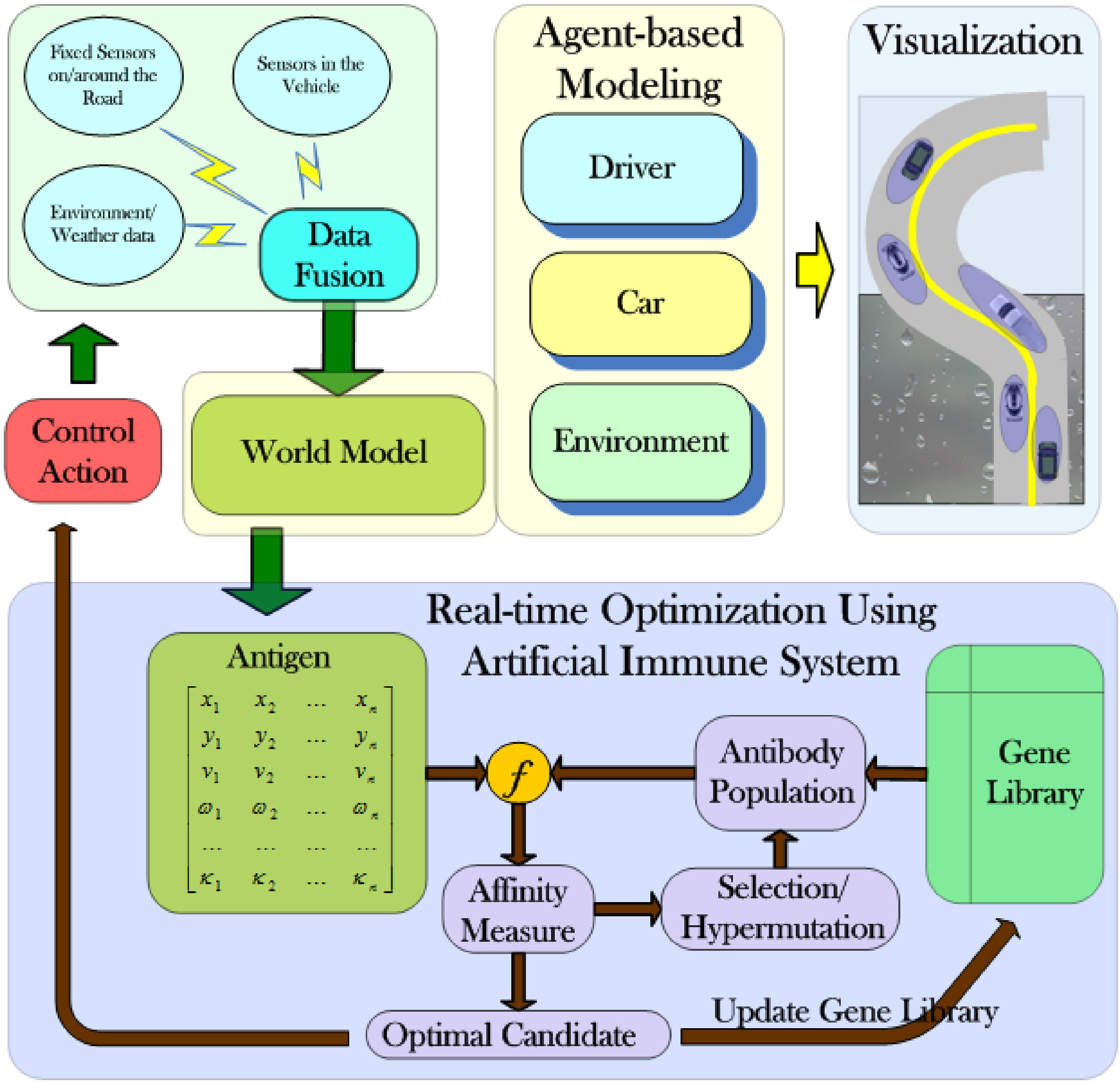


Biologically inspired approach: AIS gene library based real-time resource allocation on time-sensitive large-scale multi-rate systems

Artificial Immune Systems (AIS)

- Inspired by the principles and processes of the vertebrate immune system
  - protects the body (*self*) from invasion by harmful microbes (*non-self or Antigen).*
  - Consists of different layers of protection
    - Physical layer (skin), Biochemical layer (sweat, tears, saliva), Innate Layer (Phagocytes, static) and Adaptive Layer
  - Adaptive Layer (B-cells, T-cells, antibodies)
    - Negative Selection, Clonal Selection, Somatic Hyper-mutation etc. take place to **recognize the pattern** of new microbes and **optimize** the process of recovery
  - Exhibits lifelong learning and memory (ex. through vaccination)
  - Diverse, Distributed, Error Tolerant, Dynamic, Adaptive
- Artificial Immune System
  - Mimics *some* of the processes involved in the natural immune system, specially in the *adaptive* layer (clonal selection, negative selection and somatic hyper mutation)
  - Has been used for Learning, Anomaly Detection and Optimization tasks
  - Known to produce robust results
  - Adaptive

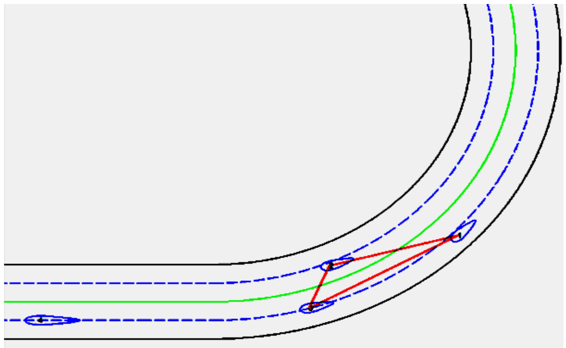
ITS using Artificial Immune Systems - Architecture



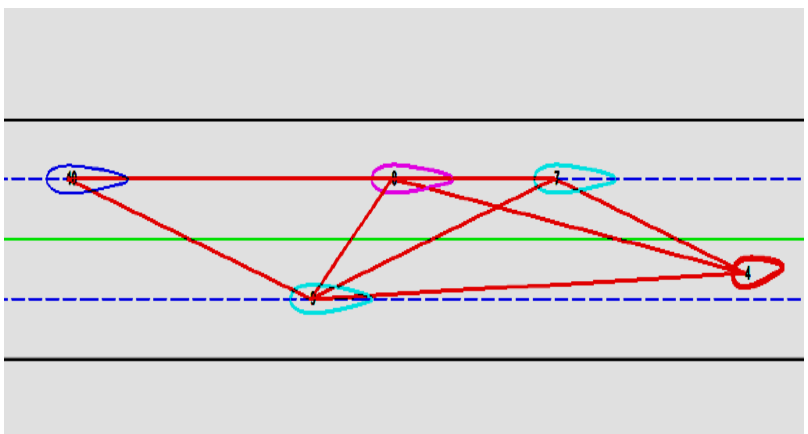
- Develop a model of the environment
- Use AIS for several ITS related functions including Path Planning, Impaired Driver Recognition, Resource Allocation
- Define antigens, antibodies, genes, affinity functions, and the adaptation for each applications
- Only the structure of the antigen and the fitness function ***f*** need to be changed to incorporate different types of pattern recognition and optimization problems

E.g., AIS in ITS for Impaired Driver Recognition

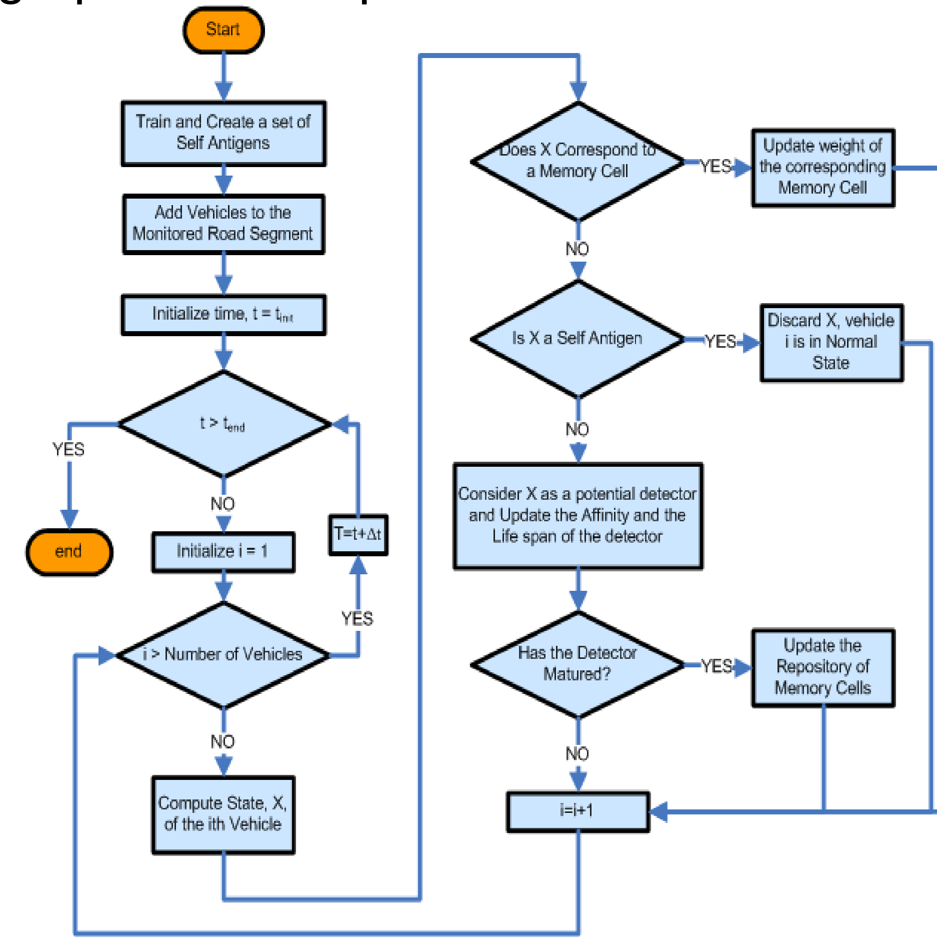
- Objective: Identify impaired drivers in a road segment
- Approach: use AIS along with graph-based representation



Graph-based representation in an ITS



Once a driver is recognized as impaired (RED), the neighboring drivers are warned (CYAN) and also resource allocation decision is made (Resource is given to the MAGENTA car)



Flow-Chart for the implementation of AIS in Impaired Driver Recognition

When, Where, and Why?

- When?
  - Now
- Where?
  - All major industries striding for high-level of performance in real-time
    - Energy, Transportation, Military, Entertainment – gaming, etc.
- Why?
  - Desires to improve performance
    - Efficiency, accuracy, reliability, resilience, cost, security, environmental concerns, competitiveness, etc.
  - Availability of technologies
    - Large-scale deployment and advancements of networks (Internet, cable, cellular, etc.)
    - Advancements in embedded systems: networked sensors, networked actuators, networked controllers, etc.
    - …

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Time-sensitive complex networked control systems challenges

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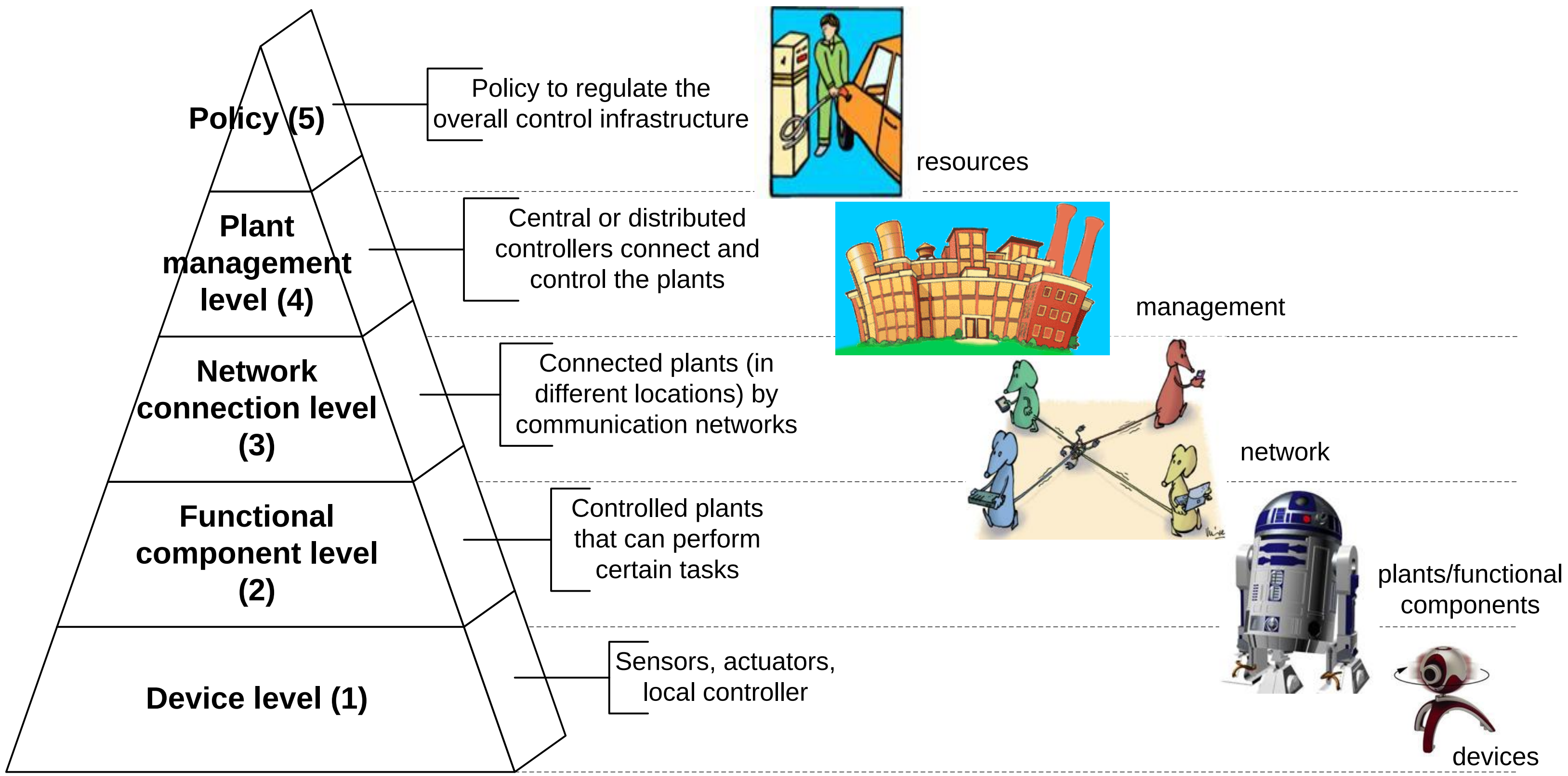
- All the challenges related to time-sensitive network control systems
- Need a higher level to regulate the entire system performance
  - Policy vs algorithms
  - All layers' interactions

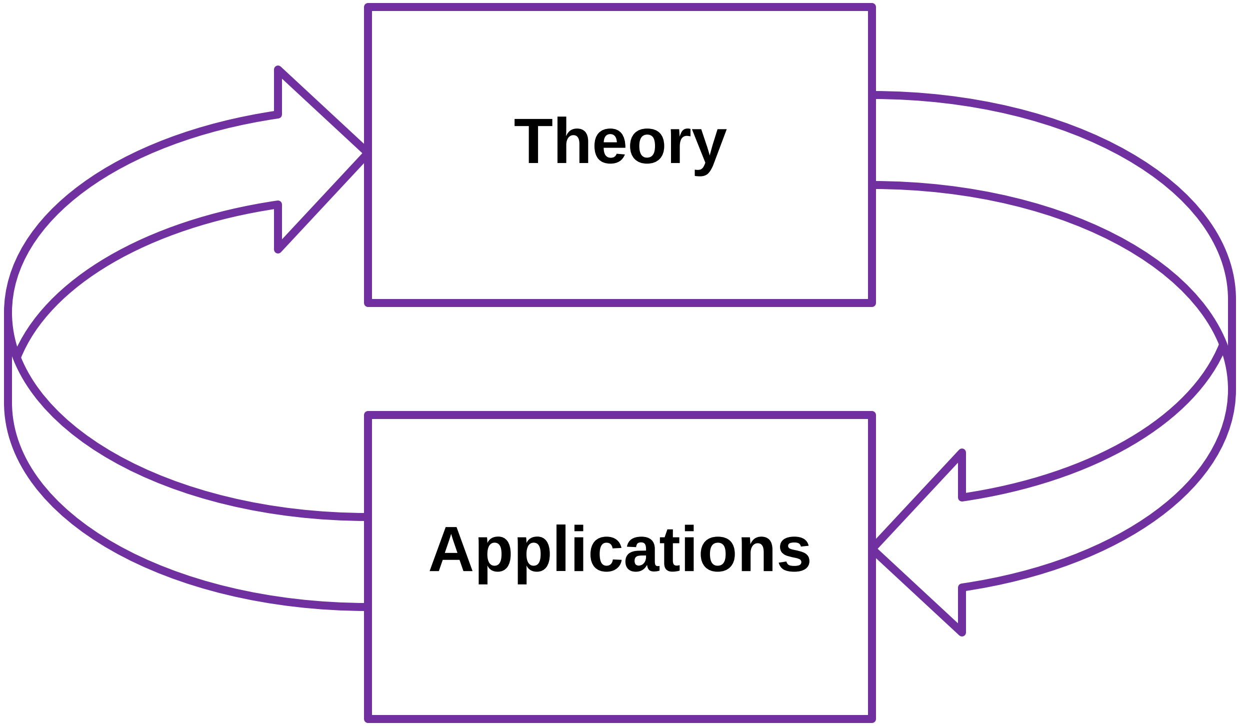


Potentially tools?

- Tools
  - Systems and Control theory
    - Distributed control, cooperative control, etc.
  - Graph/network theory
    - random network, small world, etc.
  - Biological inspired algorithms
    - ANN, AIS, Swarming, Co-evolution, etc.
  - Economic, social systems
    - Auction, consensus, supply and demand
  - Distributed algorithms
    - consensus algorithms, auction algorithms, multi-agent game theory, free-market economy, etc.
  - Etc.

Challenges – cont.

- From real-world problems to abstract problem formulations and modeling
  - How to properly formulate the complex networks mathematically so that we can apply the existing tools?
    - What are the agents, their inputs, outputs, and functions
    - What is the small world in our problems?
    - What is the antigens and antibodies in our problems?
    - What are the intelligences in our system?
    - Etc.
- Tools selection: What other tools we need to solve our complex network control problems?
- Design issues - one size does not fit all
  - Self vs whole
  - Algorithms vs policy
  - Centralized vs distributed – hybrid: what are the compositions
  - Etc.


Theory
Applications

Experience and sharing

- My top five picks of knowledge to solve time-sensitive complex network control systems
  - Domain knowledge
  - Systems and control theory – modeling, transient responses, stability analyses
  - Agent concepts, graph theory, Petri net – high dimensionality knowledge
  - Communication network – time delay, bandwidth allocations, securities
  - Large scale optimization – conventional, computational intelligence, and distributed

Summary

- More and more complex networked control systems will emerge
- More and more devices/components are emerging for complex networked systems usages
- Need good framework to assist the growth of complex networked control systems
- Need new mathematical tools/theory to guide the research/development and growth in this area
- Need to see more successful stories on applying existing tools on complex system controls to inspire their future growth

Acknowledgements

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  - NSF Collaborative Research: GOALI: AIS gene library based real-time resource allocation on time-sensitive large-scale multi-rate systems, funded by NSF 0823952.
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Thank you!